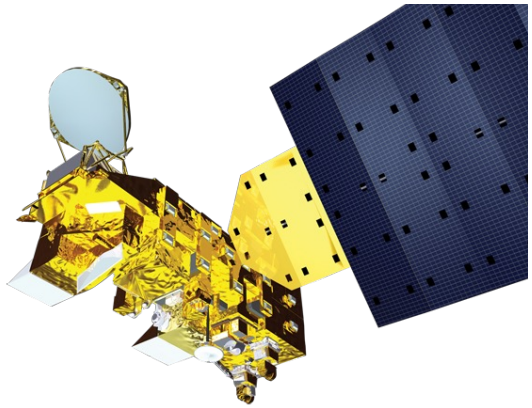

Review of Aqua Mission Status, Future Possibilities, and RFI Responses

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Lazaros Oreopoulos/Aqua Deputy Project Scientist
William J. Guit/Aqua Mission Director

NASA Goddard Space Flight Center

Presentation at the Terra, Aqua, and Aura Drifting Orbits Workshop,
given online from NASA Goddard, November 1, 2022

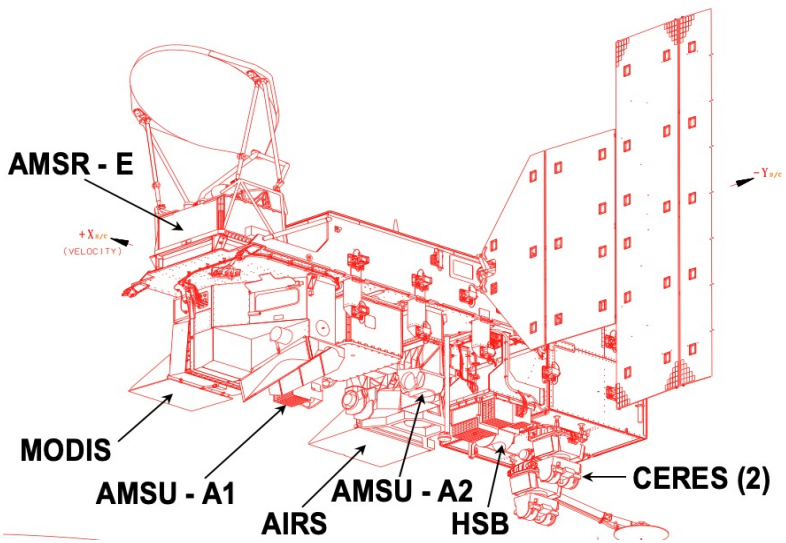
Aqua's First 20 Years On Orbit

- Launched May 4, 2002, with a design life of 6 years and six Earth-observing instruments, four still operating.
- First satellite in the A-Train and the A-Train's cornerstone until January 2022.
- Altitude of 705 km; tightly controlled orbit, with mean local equatorial crossing times (MLTs) of ~1:35 a.m. and ~1:35 p.m.
- Significant, wide-ranging accomplishments, with Aqua data used in over 20,000 scientific publications and in numerous practical applications.

Aqua Going Forward

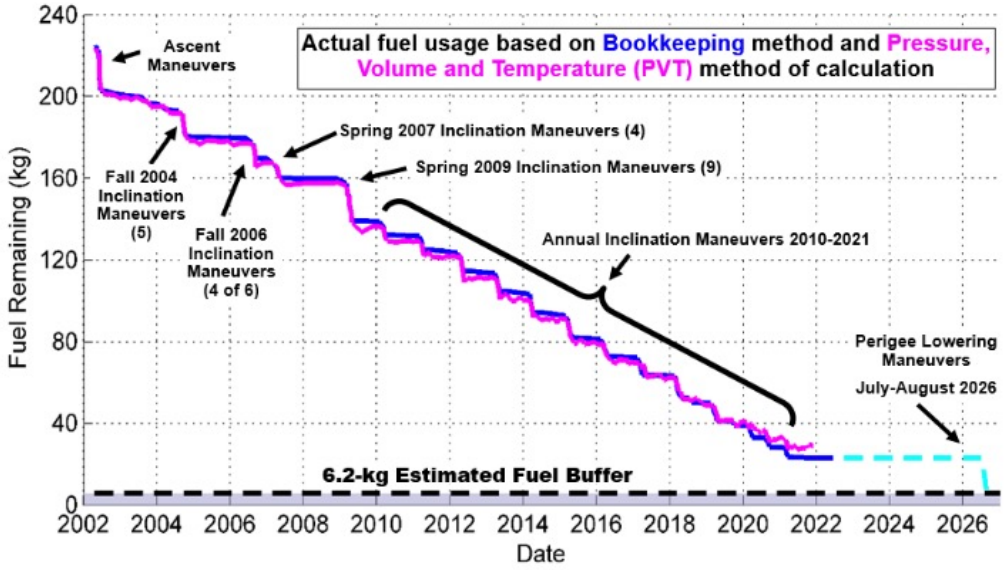
- Now in a free-drift mode (final drag makeup maneuver: 12/1/2021), with MLTs shifting to later times of day.
- Potential continuation of data collection until ~August 2026, by which time the MLTs will have drifted to ~3:50 a.m. and ~3:50 p.m.
- Exciting possibilities of new science made possible by the drifting orbits.
- Possibility of important data overlap with upcoming missions.

Aqua's Earth-Observing Instruments

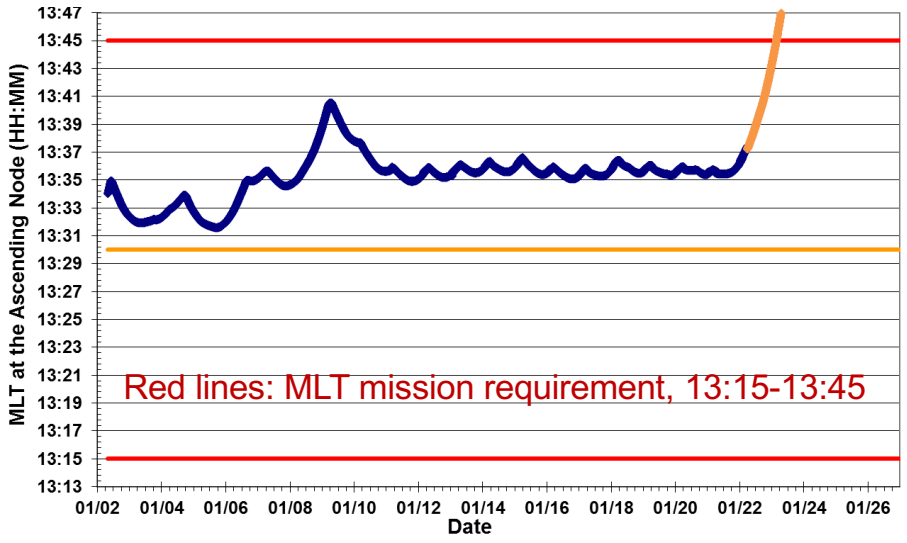


- AIRS: Atmospheric Infrared Sounder
- AMSU: Advanced Microwave Sounding Unit
- HSB: Humidity Sounder for Brazil. Provided by Brazil; no longer operating
- AMSR-E: Advanced Microwave Scanning Radiometer for EOS. Provided by Japan; no longer operating
- CERES: Clouds and the Earth's Radiant Energy System (two copies)
- MODIS: Moderate Resolution Imaging Spectroradiometer

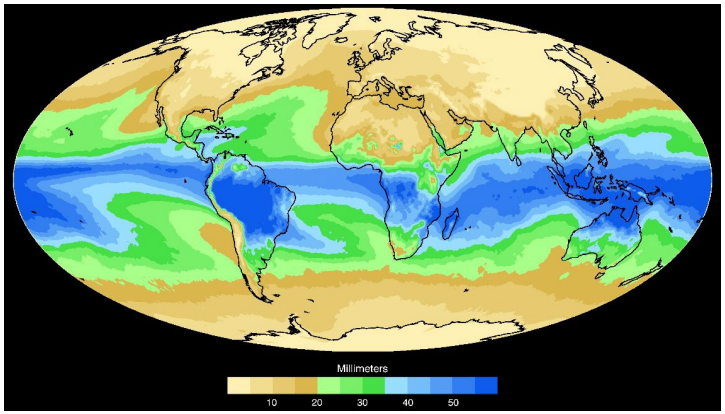
Aqua's Fuel Usage



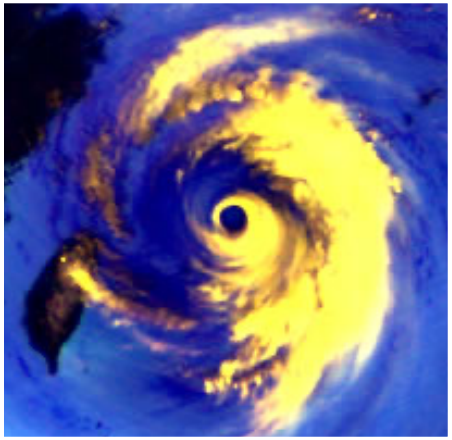
Aqua's Mean Local Time



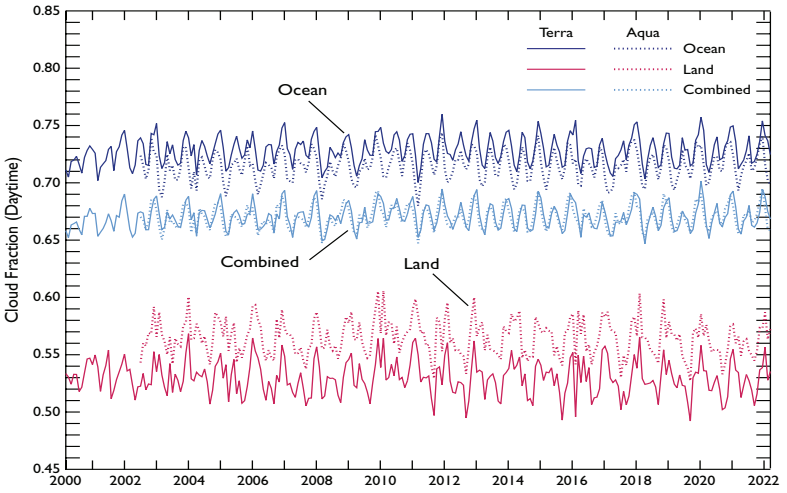
Aqua Sampler 1: Water



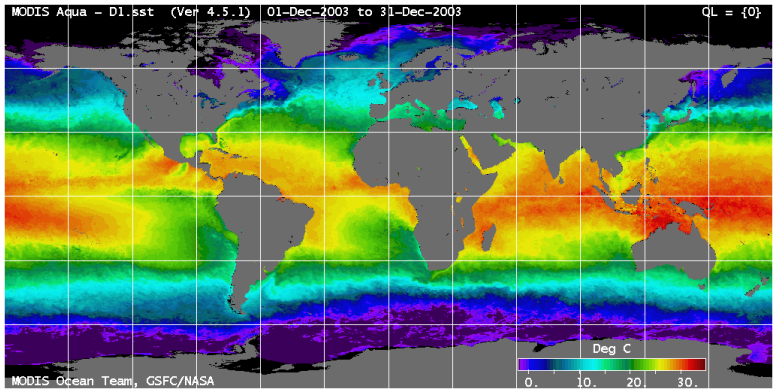
Water vapor from AIRS



Typhoon from AMSR-E

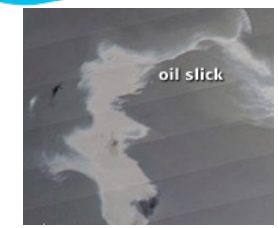


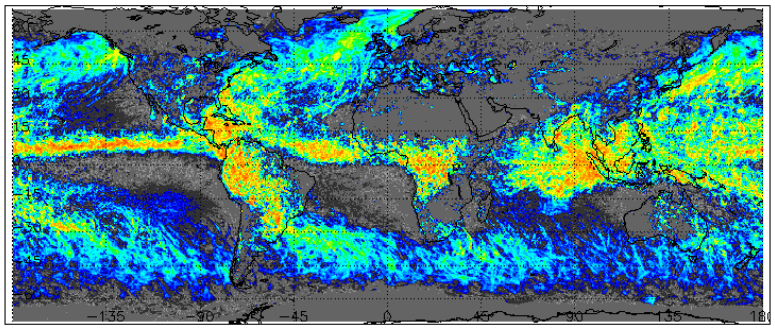
Clouds from MODIS (King et al.)



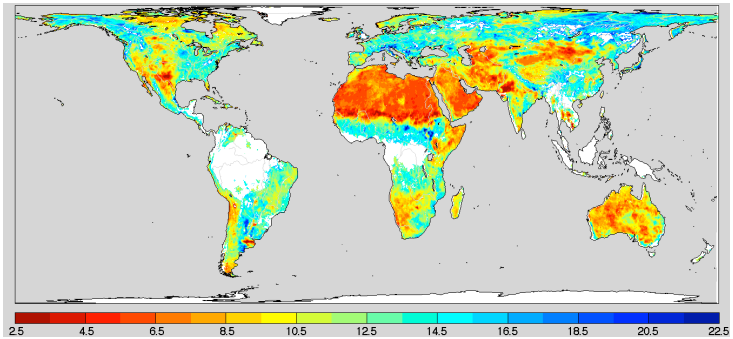
Sea surface temperature from MODIS

Oil spill from MODIS

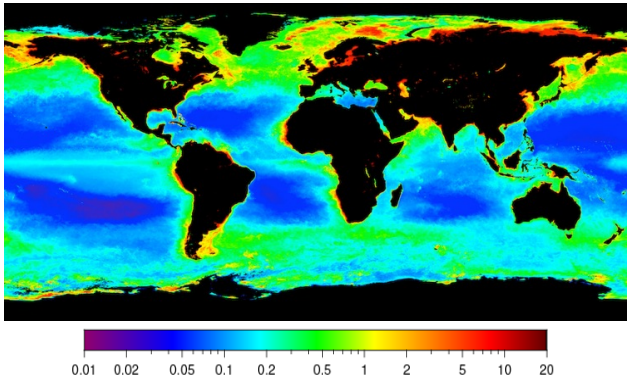




Rainfall from AMSR-E



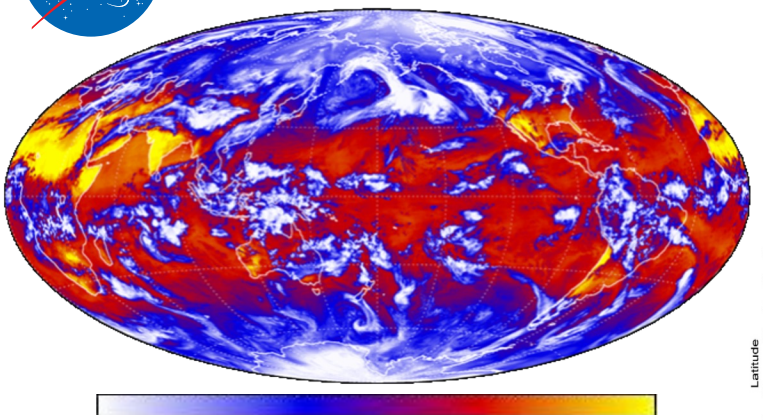
Soil moisture from AMSR-E



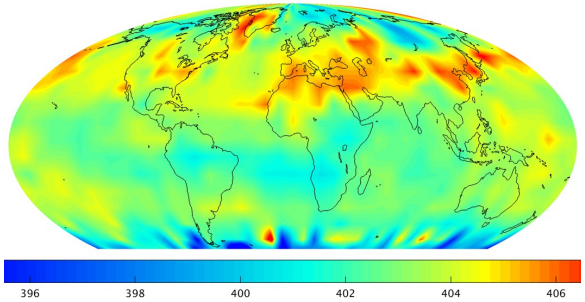
Chlorophyll-a from MODIS

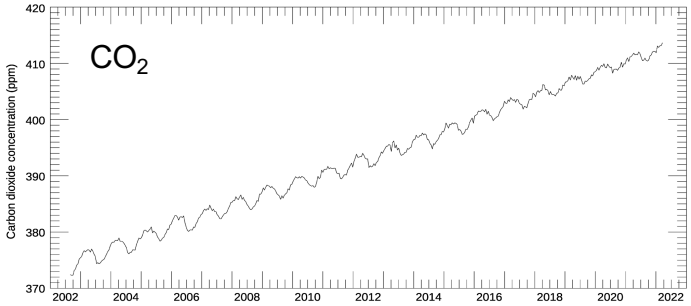
Sea ice from AMSR-E

Aqua Sampler 2: Global Change

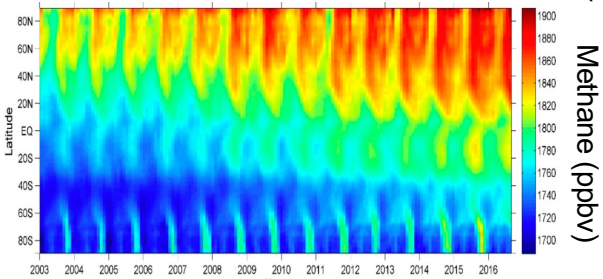


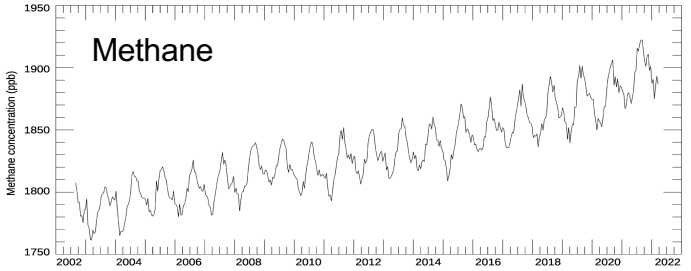
Outgoing longwave radiation from CERES



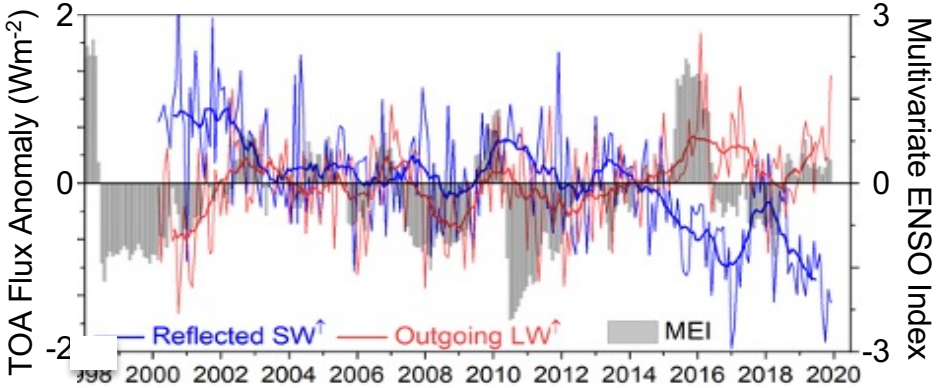


Carbon dioxide from AIRS (map from E. Olsen, plot from V. Payne)



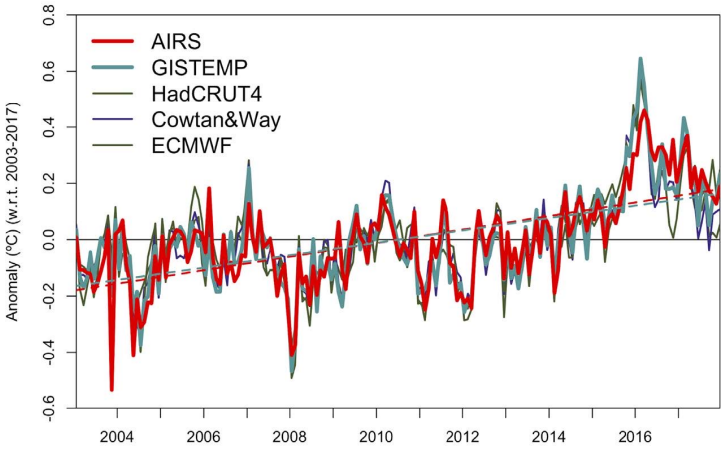


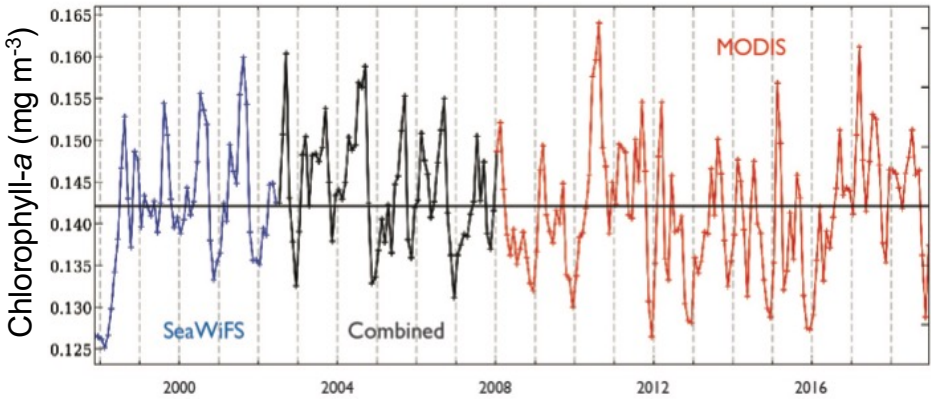
Methane from AIRS (graphic from Zou et al. 2019, plot from V. Payne)



Global TOA fluxes from CERES (updated Loeb et al. 2018)

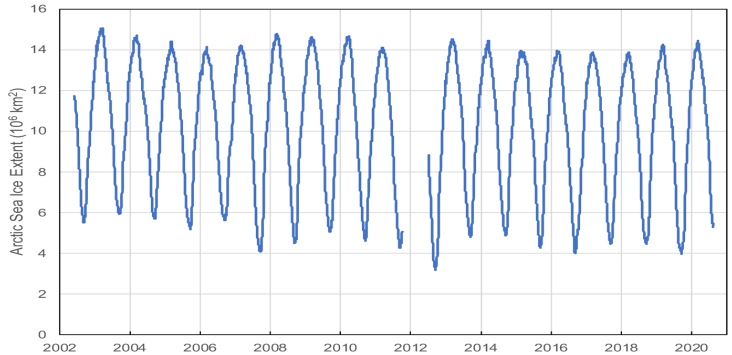
Global warming from AIRS (Susskind et al. 2019)





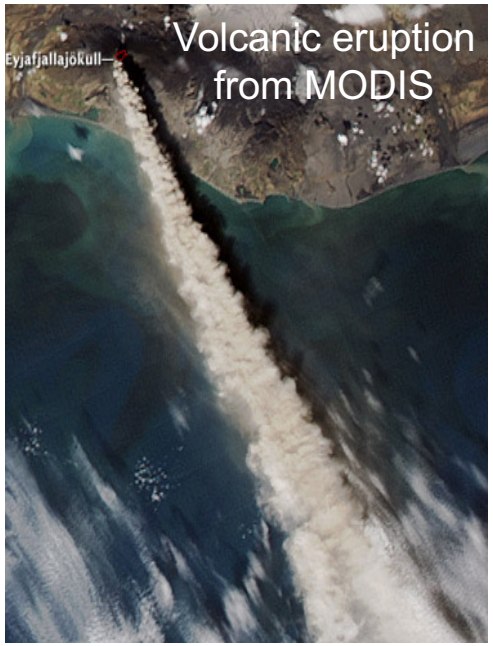
Chlorophyll-*a* from SeaWiFS and MODIS (Franz et al. 2019)

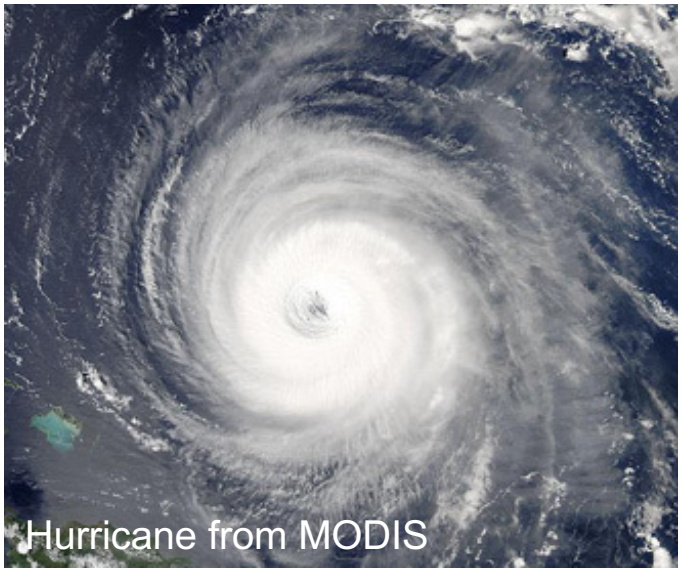
Arctic sea ice extents from AMSR-E and AMSR2



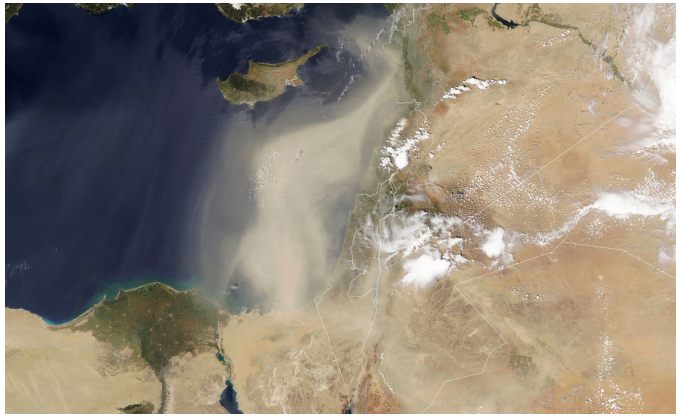
Aqua Sampler 3: Applications

"The AIRS instrument has provided the most significant increase in forecast improvement in this time range of any other single instrument."
— 2005 quote from the NOAA Administrator Conrad C. Lautenbacher, Jr.

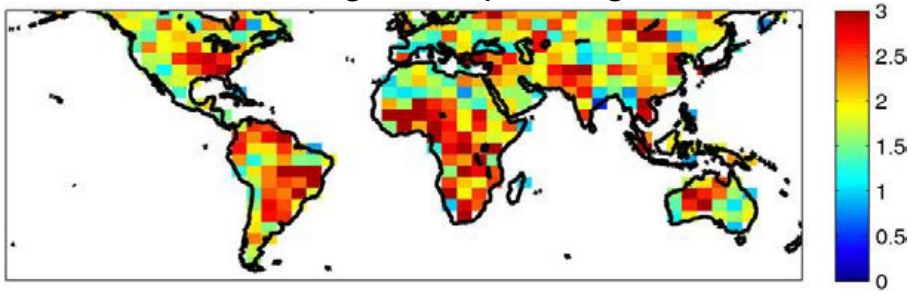




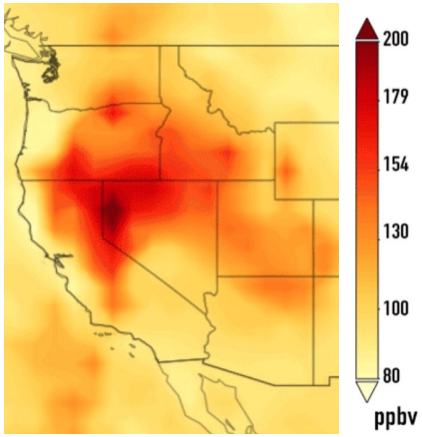
Dust storm from MODIS



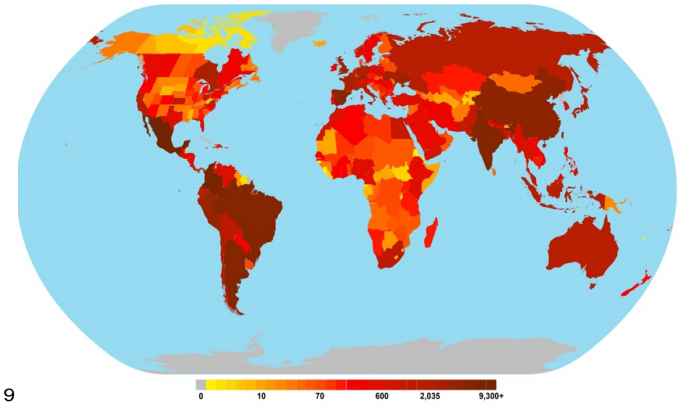
Improved lead time (in months) for early drought detection through incorporating AIRS data



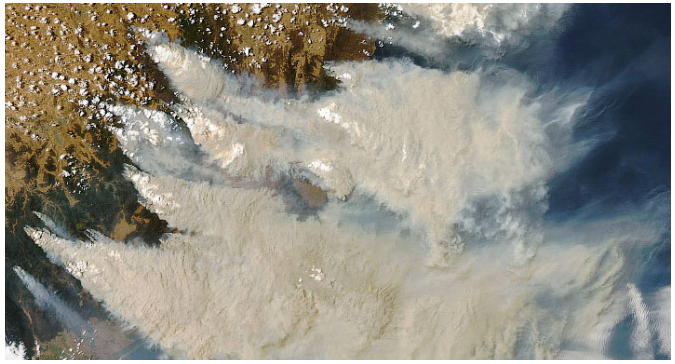
CO from AIRS data



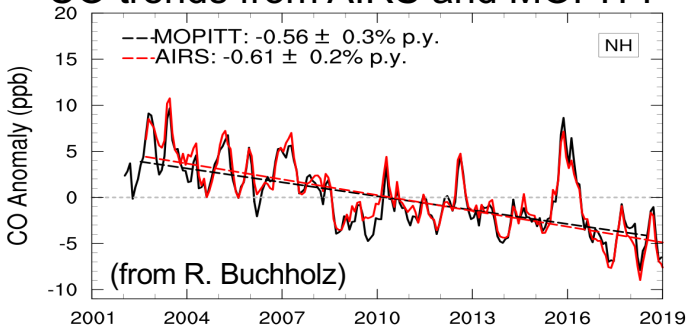
Users of CERES FLASHFlux data



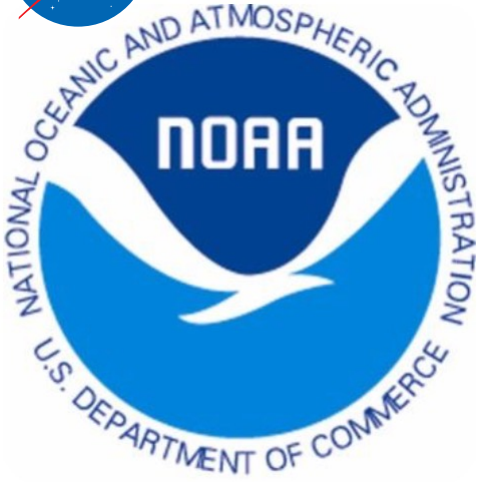
Fires and smoke from MODIS



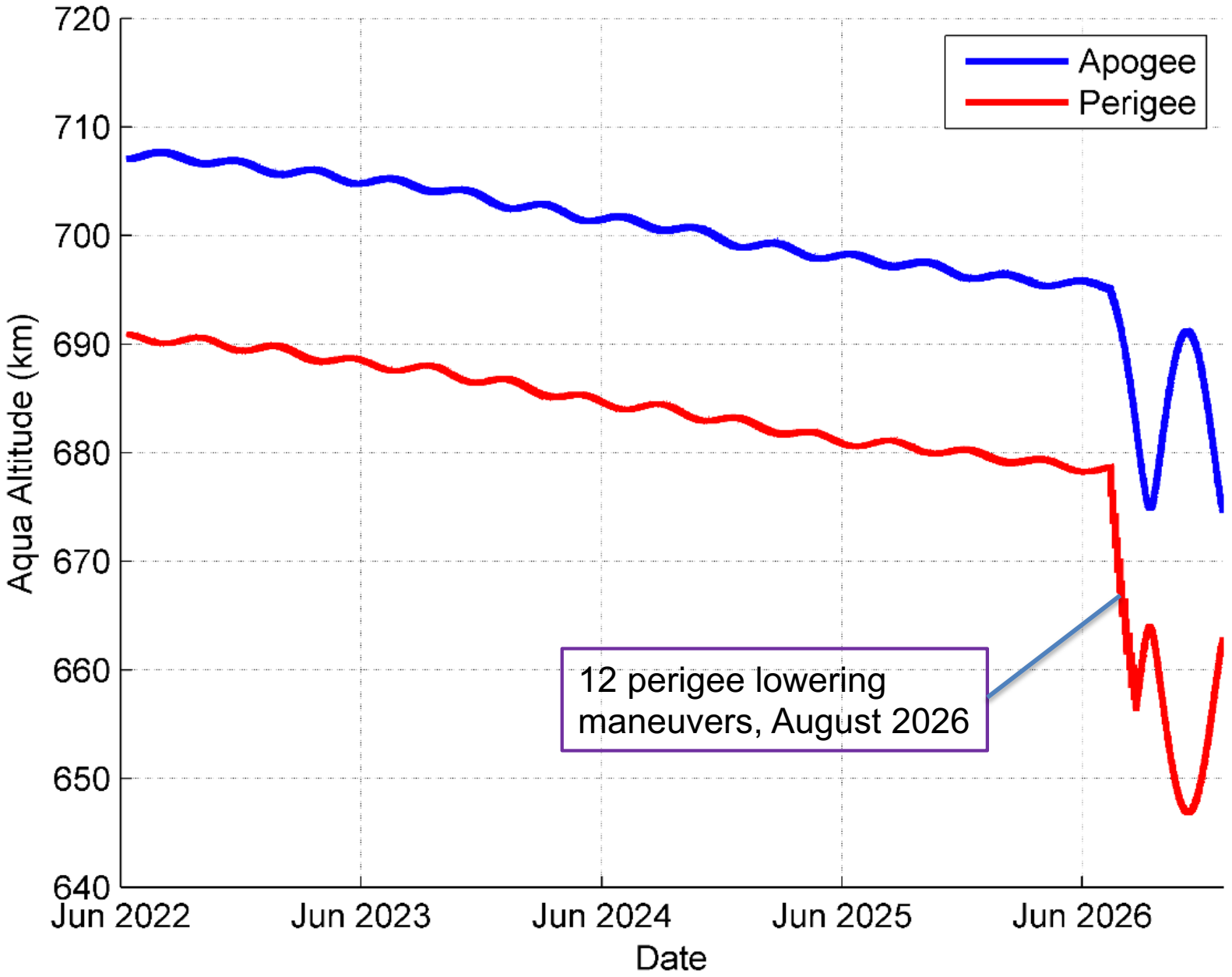
CO trends from AIRS and MOPITT



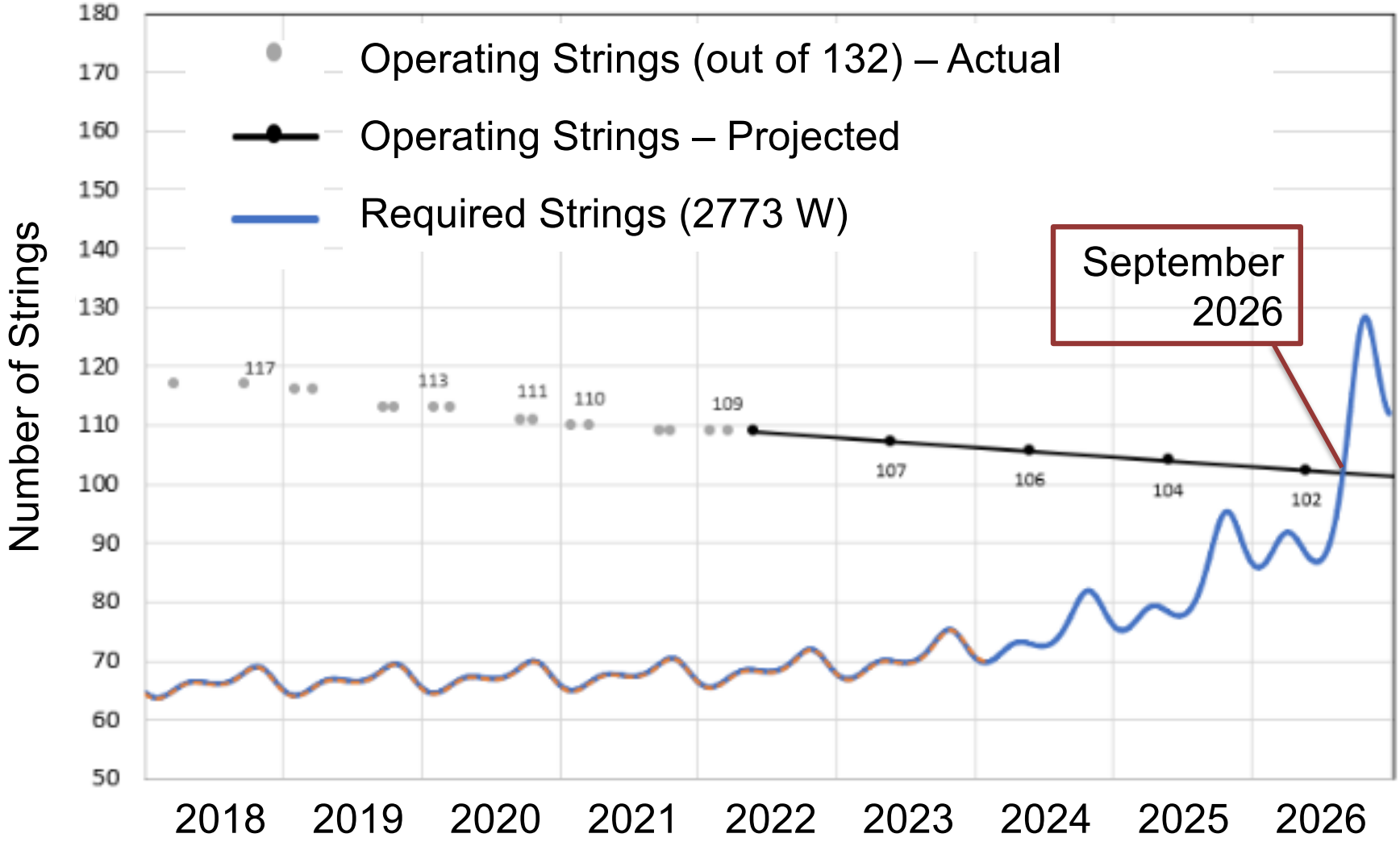
Federal Government Users of Aqua Data



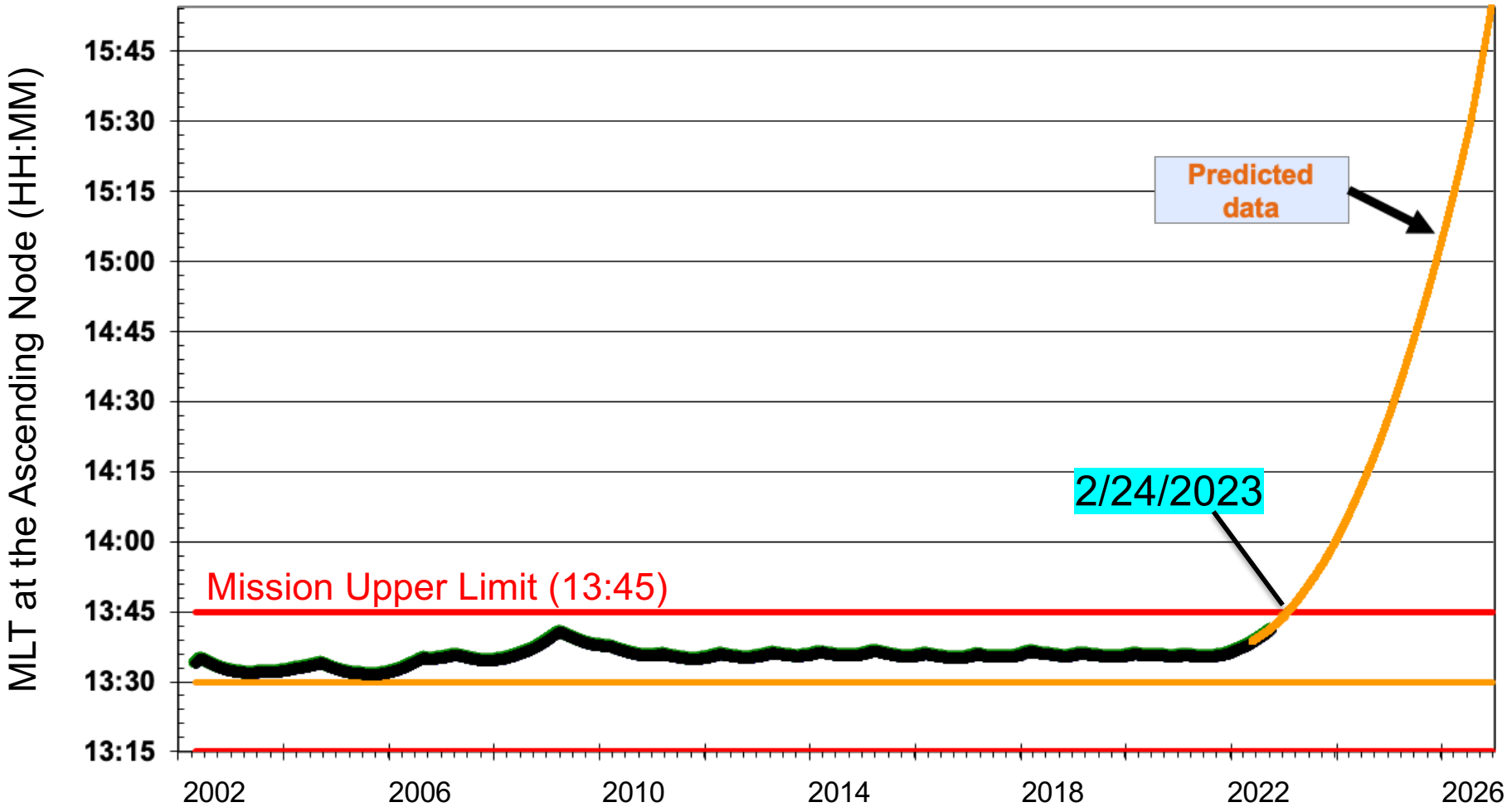
Aqua's Apogee/Perigee Predictions (if funding continues)



Aqua's Remaining Operational Strings on the Solar Array & Power Requirements



Aqua's Past and Predicted MLT at the Ascending Node



Future Possibilities if Funding and Hardware Durability Allow

- Further extension of the Aqua data sets, conceivably until August 2026.
- Continued overlap with current missions and anticipated overlap with new missions, enabling extension of the data sets beyond the period of Aqua data collection.
- Exciting new possibilities with the now-drifting MLTs.
  - Enhance understanding of diurnal cycles of atmospheric and surface phenomena.
  - Allow weather prediction centers to assess the impact of observations from different times of day.
  - Obtain data closer to the peak time of convection and severe storms, helping address key science questions on these topics.
  - Provide time-of-day information of value in designing new missions.
  - Enable accurate corrections for orbital drift in the historical record of various data sets.

Key Concepts in Aqua RFI Responses Addressing Theme 1
(a) Opportunities for Studying Diurnal Cycles and Variability

- Radiative fluxes, from CERES (Tsushima; Doelling et al.)
- Radiation and cloud cover (Norris; Smith et al.; Kato et al.; Stubenrauch et al.)
  - Reference for evaluating geostationary cloud retrievals at different times of day, from CERES and MODIS (Smith et al.)
  - Cloud properties, from AIRS/AMSU, MODIS, CERES (Stubenrauch et al.)
  - Extratropical cloud properties, from MODIS and AIRS (Naud)
- Cloud microphysics, from MODIS (McCoy et al.)
- Deep cloud formation, deep convection, shallow cloud processes, and boundary layer thermodynamics, from combined use of AIRS and MODIS (Fetzer et al.)
- Planetary boundary layer, from AIRS data combined with CrIS and IASI data from alternative times of day (Ferguson)
- Pollutants, aerosols, and clouds, from MODIS (Yuan)
- Climate and weather processes, from AIRS (Lambrigtsen)
- Fires, from MODIS (Hyer and Baker)
- Fire volatile organic compounds, from AIRS (Millet)
- Snow cover, from MODIS, CERES, and AIRS (Feldman et al.)
- Ecosystem processes such as photosynthesis, evapotranspiration, and water use efficiency, from MODIS (Xiao)
- Lake temperatures, evaporation rates, and impacts on freshwater ecosystems, from MODIS (Gao and Zhang) and heat stress in lakes, from MODIS (Hook et al.)
- Skin sea surface temperatures, from MODIS (Minnett)

Key Concepts in Aqua RFI Responses Addressing Theme 1
(b) Advantages of Atmospheric Data from Later in the Afternoon

- New possibilities for examining environmental processes leading to convection, which peaks much later in the afternoon than 1:30 p.m., enhancing the understanding of many processes and phenomena.
  - Atmospheric pre-conditions for the initiation of organized convection, from AIRS/AMSU, MODIS, and CERES (Zeng)
  - Convective processes, from AIRS temperature and humidity soundings (Elsaesser et al.)
  - High-impact convective weather, from AIRS temperature and humidity soundings (Kahn et al.)
  - Convection and thunderstorm development through combined use of AIRS at later MLTs and NOAA-20 at 1:30 p.m. (Berndt et al.)
  - Tropical cyclones and polar lows, from AIRS (Reale et al.)
  - Cumulus convection, from AIRS and CrIS (Fishbein)
  - Deep cloud formation and vertical water vapor transport processes, from coincident AIRS and MODIS (Fetzer et al.)
  - Gravity waves generated by convective storms, from AIRS (Alexander et al.)
- New opportunities opened because of the typically stronger fires in later afternoon, which loft emissions to higher altitudes, where the retrieval quality from AIRS is better due to higher spectral sensitivity, with particular attention to ammonia (Cady-Pereira) and even to such gases as methanol and ethene, which are close to and/or currently under the AIRS detection threshold (Payne et al.)
- Opportunity to study the evolution of fire plumes and their impact on atmospheric composition during the afternoon, when fire activity typically increases (Payne et al.)
- Unique opportunity to compare Aqua AIRS observations at later MLTs with CrIS observations at 1:30 a.m./p.m.
  - Value for quantifying surface wet bulb temperatures and convective evolution (DeSouza-Machado and Strow)
  - Value for examining atmospheric river events, especially when combined additionally with IASI 9:30 a.m./p.m. data (Ferguson)

Key Concepts in Aqua RFI Responses Addressing Theme 1 (c) Advantages of Surface Data from Later in the Afternoon

- Opportunity for enhanced vegetation studies, as 1:30 – 3:50 p.m. is the time during which plants often close their stomata due to water and/or heat stress, reducing photosynthesis and evapotranspiration (Xiao)
  - Explore the physiological responses of vegetation to a wider variety of conditions, especially to times of typically greater plant stress, from MODIS (Huemmrich)
  - Improve the characterization of plant stress, from MODIS afternoon evapotranspiration data (Cawse-Nicholson)
- Opportunity for enhanced fire studies, as mid-to-late afternoon is typically when fires are most common and most extreme (Morton et al.)
  - Enhanced value of Aqua MODIS observations of active fires, burned area, and fire aerosols (Morton et al.; McCarty et al.)
  - Close major gaps in our understanding of large fire behavior, from MODIS combined with 1:30 p.m. data from S-NPP and NOAA-20 (Morton et al.)
  - Evaluate the impact of fires on atmospheric composition (Payne et al.; Cady-Pereira; see previous slide)
  - Possibly produce a pre-MODIS AVHRR-based long-term record of global fire activity, by utilizing the Aqua drift to later MLTs and Terra drift to earlier MLTs (Giglio and Schroeder)
- Opportunities from obtaining morning temperatures closer to the daily minimum and afternoon temperatures closer to the daily maximum
  - Allows more accurate diurnal land-surface temperature ranges, from MODIS (Hall et al.; Hulley et al.; Ruston and Auligne), and thereby improved characterization of urban heat stress and societal vulnerability (Hulley et al.)
  - Provides a better daily average for SSTs and ocean color, from MODIS (Upton)
  - Provides improved estimates of the diurnal range of lake temperatures, from MODIS, opening possibilities for enhanced studies of the impacts of temperature on lake biodiversity (Hook et al.)
- Opportunity for enhanced drought studies from AIRS, due to the nighttime MLT being closer to sunrise (Roundy)

Key Concepts in Aqua RFI Responses Addressing Theme 1

(d) Additional Unique Opportunities Resulting from the Orbital Drift

- Improve the CERES angular distribution models (ADMs), for improved radiance-to-flux conversions and reduced flux uncertainties (Su et al.)
- Demonstrate the importance of MLT for global and regional applications, e.g., from AIRS (Ruston and Auligne)
- Address the impact of solar zenith angle and different viewing angles on MODIS and CERES data (Zeng)
- Decouple the impacts of pixel size and sun-satellite geometry from the impacts of the diurnal cycle of clouds, from MODIS (Wang and Meyer)
- Pursue additional opportunities arising from having Aqua drift in MLT while S-NPP and NOAA-20 remain at 1:30 p.m. MLT
  - Provides a 1:30 p.m. baseline for the Aqua observations with drifting MLT (Fetzer et al.)
  - Enables development of algorithms to correct for orbital drift in the historical record, potentially markedly improving the quality of 40-year AVHRR records (Loeb et al.; Doelling et al.)
- Update and refine MODIS cloud vertical-structure algorithms based on periodic overlaps of the drifting Aqua with the upcoming EarthCARE mission, planned for launch in 2024 (Haynes)
- Compare Aqua and EarthCARE measurements when Aqua's MLT reaches EarthCARE's 2:00 p.m. MLT (Loeb et al.)

Key Concepts in Aqua RFI Responses Addressing Theme 1
(e) Potential Model Improvements

- Cloud parameterizations, from AIRS (Elsaesser et al.) and from AIRS, AMSU, CERES, and MODIS (Stubenrauch et al.; Elsaesser et al.)
- Representation of gravity waves in high resolution atmospheric models, from AIRS and the Aura MLS (Ern)
- Simulation of the Quasi-Biennial Oscillation, helped by improved knowledge of convectively generated gravity waves, from AIRS (Alexander et al.)
- Global chemistry transport models and chemistry-climate models, from AIRS (Payne et al.)
- Fire emission parameterizations, from AIRS (Millet)
- Wildfire parameterizations in air quality models, from MODIS (McCarty et al.)

Key Concepts in Aqua RFI Responses Addressing Theme 1 (f) Desired Data Overlap with Upcoming Missions

- CERES and MODIS overlap with CLARREO Pathfinder, planned to operate from the ISS in 2024 (Loeb et al.; Shea and Bhatt)
- MODIS overlap with EarthCARE, scheduled to launch in 2024 (Haynes; Loeb et al.)
- MODIS overlap with PACE, scheduled to launch in 2024 (Loeb et al.)
- AIRS overlap with future sounders, e.g., on JPSS-2, for continued climate monitoring (Roman et al.)
- MODIS cloud microphysics data overlap (or at least lessening the gap) with the Atmospheric Observing System (AOS) (McCoy et al.)
- Eliminate or reduce data gaps with upcoming records
  - Decrease the gap between CERES and Libera (Zagoni)
  - Lessen the chance of a data gap in the Earth Radiation Budget climate data record, from CERES (Loeb et al.; Mauritsen)
  - Recognize that assimilation of new satellite data will be more difficult with limited or no overlap with the high-quality, well-calibrated Terra/Aqua/Aura benchmark datasets (Engelen et al.)
- "… if the three satellites are decommissioned before new platforms that monitor the Earth's energy imbalance are in place, then the data record will be irreparably broken, and with it, humanity will miss important data to guide its efforts to limit climate change" (Mauritsen)

Key Concepts in Aqua RFI Responses Addressing Theme 1 (g) Additional Opportunities with the Longer Record

- Allow studies of the effect of sunspots and solar magnetic fields on equatorial high thin cirrus clouds with an Aqua data set that covers a full 22-year sun cycle (Borbas et al.)
- Allow studies of the effects of additional El Nino and La Nina events (Borbas et al.)

Key Concepts in Aqua RFI Responses Addressing Theme 2
(a) Continued and Improved Forecasting

- Weather forecasting, importance of AIRS/AMSU (Engelen et al.; Berndt et al.; Zhang et al.; Ruston and Auligne)
  - AIRS was the first hyper-spectral infrared satellite sensor used operationally and continues to be a vital resource for weather forecasting (Engelen et al./ECMWF)
  - AIRS is the backbone of the ECMWF global reanalysis ERA5 (Engelen et al.)
  - AIRS data are used operationally by most global NWP centers, and the significant impact of AIRS data in data assimilation has been established (Zhang et al./WMO; Hyer and Baker/NRL; Ruston and Auligne)
- Weather forecasting, importance of AIRS and MODIS water vapor measurements (Forsythe)
- Weather forecasting enhancements from AIRS with the shift to later MLTs, closer to morning aviation and car rush hours and afternoon car rush hour, with benefits also from the greater time lag between AIRS and CrIS (Ferguson)
- Weather forecasting enhancements through incorporation of MODIS polar winds (Hyer and Baker; Zhang et al.), including operational NWP by the U.S. Navy (Hyer and Baker)
- Forecasting of tropical cyclones and polar lows, from AIRS (Reale et al.)
- Ocean forecasting, from MODIS (Upton)
- Precipitation forecasting by the Global Precipitation Climatology Project, enhanced by AIRS (Behrangi et al.)
- Flu forecasting, from AIRS humidity data (Thrastarson et al.)
- Air-quality forecasting, from AIRS (Payne et al.)
- Drought forecasting, from MODIS (Cawse-Nicholson) and AIRS (Roundy; Farahmand et al.)
- Madden Julian Oscillation (MJO) forecasting, to be enhanced by mid-afternoon AIRS (Fetzer et al.)
- Pre-convective forecasting, to be enhanced by mid-afternoon AIRS (Berndt et al.)

Key Concepts in Aqua RFI Responses Addressing Theme 2
(b) Continued Monitoring

- Earth radiation budget, from CERES (Zhang et al.)
- Aerosols, from MODIS (Chin)
- Air pollution, from MODIS, enhanced by the Terra morning MLTs and Aqua afternoon MLTs moving closer to rush hours (McCarty et al.)
- Fires, from MODIS (Jacklyn/Australia; Zhang et al./WMO; Morton et al.; Giglio and Schroeder)
- Water quality, agriculture, floods, fires, and air quality, from Aqua, Terra, and Aura (Follette-Cook et al.)
- The ongoing megadrought in the western U.S. and its effects on agriculture, water supply, and wildfires, from MODIS; "The continuity of the MODIS ESDRs should not be disrupted during this critical period of apparent accelerating climate change in the US West" (Hall et al.)
- Climate variability and climate change, from AIRS; "the additional years provide a chance to reach statistical significance for more regions of the globe" (Roman et al.)

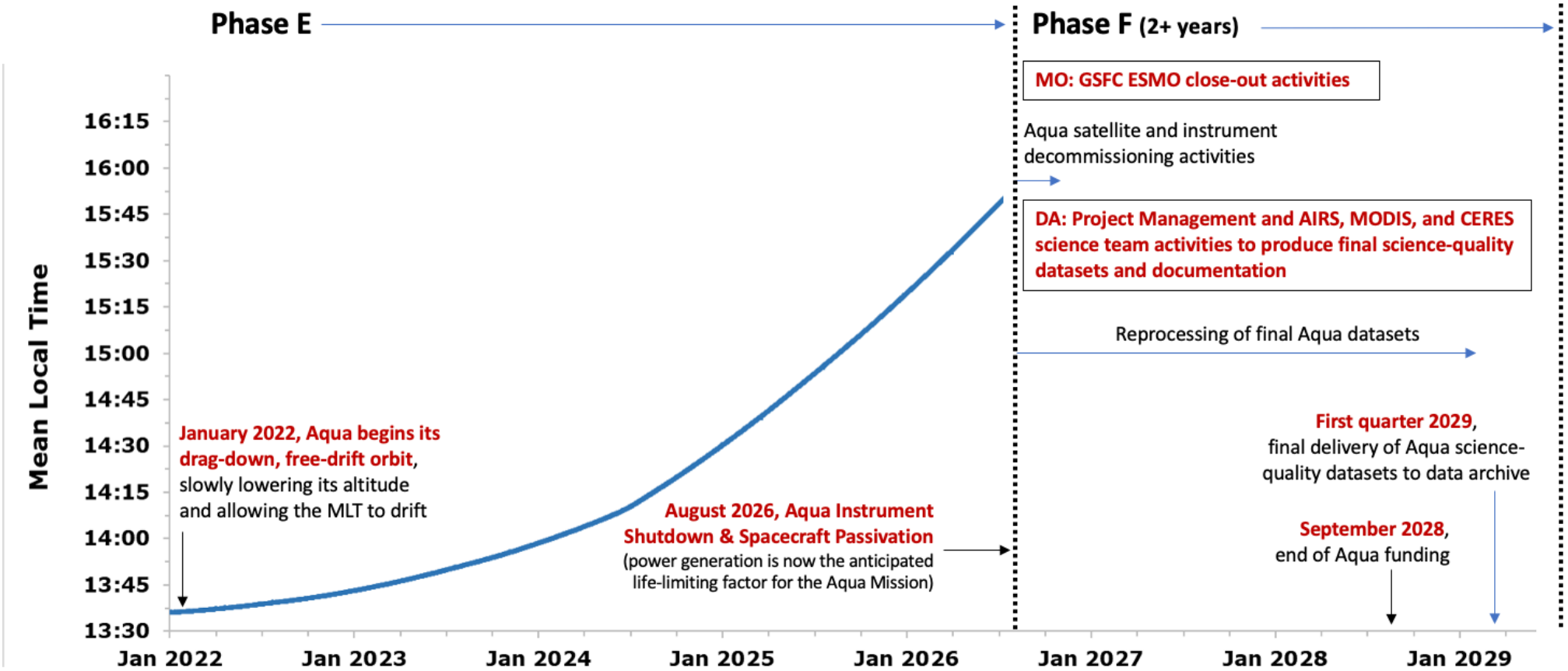
Key Concepts in Aqua RFI Responses Addressing Theme 2
(c) Value for Future Satellite Missions and Field Campaigns

- Guidance for future satellite mission design, from MODIS (Yuan) and AIRS (Fishbein)
- Value of AIRS temporal sampling during orbital drift to the planning of future hyperspectral IR sounders, e.g., on GeoXO (Reale et al.)
- Value of continued MODIS band 17 measurements for evaluating proposed bands for GeoXO Imager (GXI) (Haynes)
- Desirability of MODIS data during the October-November 2023 NASA-funded BioSCape airborne campaign in South Africa (Cardoso et al.)
- Use of MODIS data for scientific cruise support (Upton)

Key Concepts in Aqua RFI Responses Addressing Theme 2
(d) Additional Applications

- Use of MODIS data for search and rescue operations (Upton)
- Use of MODIS lake-evaporation data for water management (Gao and Zhang)
- Use of AIRS data for rapid-response science, as with the January 2022 rapid response to the Hunga Tonga-Hunga Ha'apai eruption (Alexander et al.)
- Potential use of CERES and MODIS data matched to geostationary cloud observations over a larger portion of the diurnal cycle to improve calibration of geostationary observations (Norris)
- Potential use of MODIS data from MLTs closer to the time of maximum land surface temperature to improve the issuance of heat warnings (Hulley et al.)
- Possible use of MODIS cloud microphysics data at different MLTs for examining the feasibility of marine cloud brightening as a geoengineering tool (McCoy et al.)

Aqua Mission Timeline if Maximally Extended



DA = Data Analysis
ESMO = Earth Science Mission Operations
GSFC = Goddard Space Flight Center
MO = Mission Operations